

## Abstract

Cooperation is gaining importance in different fields of process management due to highly complex network structures. Therefore, it is not sufficient to plan operations in terms of isolated decision making. While examining cooperation, many decision problems arise; e.g., choosing the right partners, evaluating the success of a cooperation, allocating costs and profits among the partners. In particular, the latter topic is of great importance because a right allocation ensures stability and fairness in a cooperation.

Shale Gas industry demands a large amount of fresh water in a relative short period of time. This water is used in drilling and hydraulic fracturing activities. Typically, between 10500–21500 m<sup>3</sup> (3–6 million US gallons) of water per well (Yang et al. 2014). After the hydraulic fracturing, part of this water returns to the surface as flowback water. The amount of water that returns to the surface ranges between 10 and 70% of the initial water demand (Hammond and O’Grady 2017), depending on different factors such as shale play geology, number of stages in the drilling, chemical composition of the shale play, etc. The flowback water composition is also site dependent, but it always includes part of the additives added to the fresh drilling water (friction reducers, proppant, biocides, surfactants, etc.) and a high concentration of dissolved solids (TDS) that can reach values above 200,000 ppm (sea water is around 35,000 ppm). Flowback water can be directly (or, if necessary, with some degree of treatment) reused for further fracking activities inside the same wellpad; it can be sent to other wellpads also to be used for fracking: it can be treated to be recycled for other uses: or it can be conveniently disposed. The water treatment can be accomplished by an onsite facility or sent to a centralized plant.

If different companies are working in the same shale zone and their shale pads are relatively close, then there exists the possibility of cooperation in order to minimize costs. Cooperation includes the possibility of sharing fresh water transportation costs; water recycled among different well pads (owned by different companies) reducing the total demand of fresh water and, consequently, the transportation costs; and building and sharing onsite water treatment facilities. In addition, the fracturing schedule can be adapted among different wellpads to maximize the water reuse.

Developing a mathematical model for the ‘grand coalition’ is as difficult as modeling the water management of a single company formed by all the partners. In other words, we could consider a single large company formed by all the partners. In the literature there are different models that deal with this problem (see for example Drouven et al., 2017). The problem consists in how to impute costs (or profits) to each one of the players (companies involved in the cooperation) in such a way that any partner or sub-coalition of partners have an incentive for remaining in the grand coalition.

The core is a central concept in game theory (Gillies, D. B., 1959). The core is formed by all the imputations (share costs) for which there is no a sub-coalition that can obtain better results than the grand coalition. The core is then formed by the set of imputations that are efficient and stable. An imputation is efficient if the total cost is distributed among all the partners and it is stable if the principles of individual rationality –a single player has lower (or at least equal) costs while cooperating than when acting alone– and coalitional rationality –the imputation to each sub-coalition in the grand coalition must be lower or equal than when they act without the rest of the partners– are met.

The objective is to get an imputation of costs inside the core. The major difficulty lies in the fact that in a game with  $N$  players the number of total sub-coalitions is  $(2^N - 1)$ , and it is not feasible (or at least practical) to solve an optimization problem for each sub-coalition.

In this paper we solve the problem by a row generation approach. First, a master problem is solved using some sub-coalitions (i.e. coalitions formed by individual players). The solution of the master problem provides a possible imputation. Then, fixing the imputation obtained in the last master problem, we solve an extended water management problem that searches for a coalition that violates most of the stability constraints. If such a coalition exists, the master problem is then updated and the procedure is repeated until we get an imputation inside the core.

In this work we present a case study with 6 players which shows that it is possible to solve the problem by solving only a small fraction of sub-coalitions.

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